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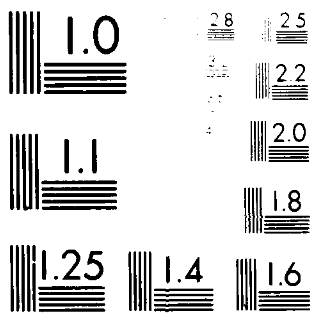

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

OPTICAL SCINTILLATION MEASUREMENTS FOR
SINGLE AND FOLDED PATHS

by

Thomas Joseph Hodgini

March 1982

Thesis Advisor: E. C. Crittenden, Jr.

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Optical Scintillation Measurements for Single and Folded Paths

by

Thomas Joseph Hodgini
Captain, United States Army
B.S., United States Military Academy, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
March 1982

Author: Thomas J. Hodgini

Approved by: E. C. Crittenden, Jr. Thesis Advisor

Edmund A. Milne Second Reader

Chairman, Department of Physics

William M. Tolles Dean of Science and Engineering

ABSTRACT

A method of measuring scintillation of two laser beams propagating along single and folded optical paths has been devised, tested, and satisfactorily utilized. The system was utilized experimentally to verify theoretical predictions of the correlation of the two paths as a function of the relative path geometry. The apparatus utilized alternating optical pulses from the two paths. The detection system employed two signal processing channels with electronic switching to permit sampling alternating source pulses with a time separation of 0.30 milliseconds. Several equipment trials and one field experiment were conducted. The results demonstrated good correlation with the theory previously developed in an accompanying project.

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ACKNOWLEDGEMENT

The author would like to express his appreciation to the Pacific Missile Test Center, Point Mugu, California, for their invaluable equipment support, a major factor in the successful completion of this project.

I. PROBLEM DESCRIPTION

A. BACKGROUND

The increasing interest of laser technology in applications such as satellite communications using a laser beacon, the pointer-tracker problem, and the potential of describing pollutants in the atmosphere with a laser beam and corner cube reflector, makes it desirable to have the capability of predicting the statistics of the propagation of a laser beam through a folded (two-way) path.

Atmospheric turbulence, beam wander, beam spread, scintillation, and other phenomena, affect laser beam propagation. Of these phenomena, scintillation is often selected as a parameter for measuring atmospheric turbulence.

Much experimental and theoretical work has been done on the prediction of the effect of atmospheric turbulence along a one-way path and it is believed that this is now fairly well understood. The problem of the folded path, the subject of several works during the past decade, is less understood. The development and testing of a procedure by which the statistics of the received irradiance of a one-way path could be compared to a folded path was the main goal of this experiment.

B. THEORY

Scintillation is random irradiance fluctuation at an observation point caused by random ray bending and interference. It is due to changes of the index of refraction, a function of temperature and pressure, along the path of propagation. The average index is

$$n = 1.0 + \frac{77.6\ P}{T}\left(1 + \frac{.0075}{\lambda^2}\right) X\ 10^{-6} \tag{1}$$

where n = Index of refraction,

P = Pressure,

T = Temperature,

λ = Wavelength.

In the weak turbulence regime an accepted statistical measurement of scintillation is the normalized log-intensity variance [Ref. 1] given by

$$\sigma_{IN}^2 = 0.52\ k^{7/6}\ L^{11/6}\ C_n^2 \tag{2}$$

where $k = \frac{2\pi}{\lambda}$,

L = Path length,

C_n^2 = Refractive-index structure parameter.

Equation 2 is valid for the turbulence strength encountered during the experimental work.

The primary motivation of this work was the verification of the theoretical predictions made by Ze'evi [Ref. 2] in which he calculated the expected correlation of a folded path to a one-way path. His results revealed a relationship between the variance of the fluctuations of the phase over a folded path and a one-way path as a function of the geometry of the system (Fig. 1), given by

$$\phi_F^2 = 2\,\phi_R^2\,[1 + f(\theta, R, L_o)] \tag{3}$$

where ϕ_F^2 = Variance of the phase fluctuations over a folded path,

ϕ_R^2 = Variance of the phase fluctuations over a one-way path,

L_o = Outer scale of turbulence,

R = Distance between the source or detector and the target,

2θ = Angle between the beam from the source and the reflected beam to the target.

Furthermore, he stated that for $R/L_o \geq 500$ and $\theta < 5°$

$$f(\theta, R, L_o) = f(y_o)$$

where
$$y_o = \frac{R \sin 2\theta}{L_o} \simeq \frac{D}{L_o} \tag{4}$$

D = Distance between the source and the detector.

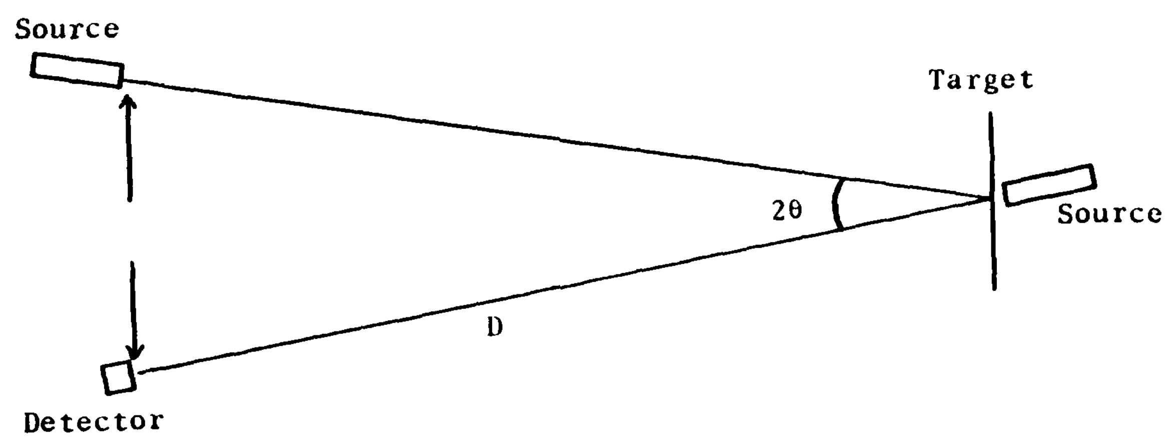


Figure 1. Diagram of Geometry of the System

In calculating $f(y_o)$ as a function of y_o, he predicted that as y_o increased from zero (D=0) to large values, $f(y_o)$ decreased from 1.0 and slowly approached zero (Fig. 2). Knowing that the statistics of a one-way path and folded path are independent for $2\theta = 90°$, one could choose an appropriate fraction of the maximum $f(y_o)$ value, say 10%, and establish the corresponding point for y_o as a characterizing value.

A major portion of this experiment was devoted to testing the equipment and procedures to ensure adequate data could be collected for the folded path versus one-way path measurements. Two possible sources, a GaAs laser and a HeNe laser, were available to be used in the experiment. Because the GaAs laser is a non-coherent source while the HeNe is a coherent source, it was uncertain if the GaAs could be used as one of the sources. With the assumption of frozen turbulence, and using equation 2, the ratio of the log intensity variances of the HeNe to the GaAs should be approximately 1.5:

$$\frac{\sigma^2_{HeNe}}{\sigma^2_{GaAs}} = \left(\frac{k_{HeNe}}{k_{GaAs}}\right)^{7/6}$$

since C_n^2 and z are equal for both, and

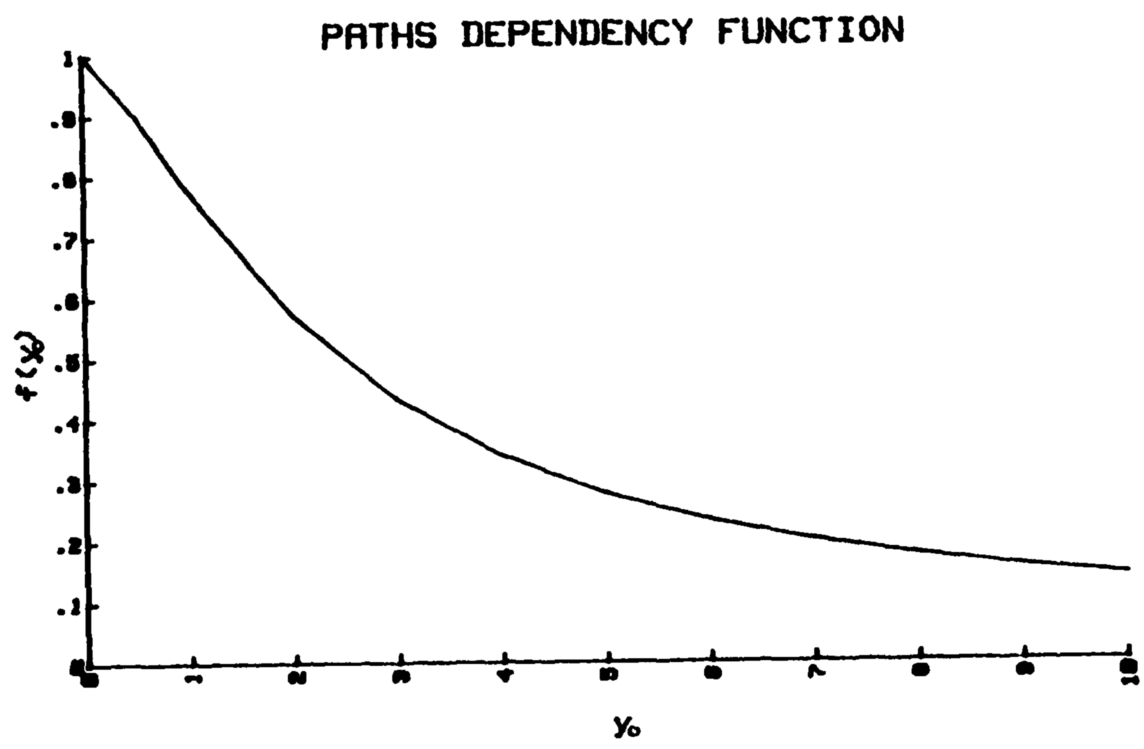


Figure 2. Graph of $f(y_o)$ versus y_o

$$\frac{\sigma^2_{HeNe}}{\sigma^2_{GaAs}} = \left(\frac{.9050}{.6838}\right)^{7/6}$$

$$= 1.518$$

The criterion established to use both the GaAs laser and the HeNe laser as sources were that measurements of the variance of the two sources along identical paths would yield a ratio of about 1.5 with a high degree of correlation. Similarly, two HeNe laser sources or two GaAs sources propagating along the same path should yield a ratio of about 1 with a high degree of correlation.

II. EXPERIMENTAL APPARATUS

A. GENERAL

Since there has been an active and continuing research effort in the area of the effect of the turbulent atmosphere on the propagation of Electromagnetic signals at the Naval Postgraduate School [Ref. 3], much of the equipment required for this experiment was immediately available. In addition to adding components to the system already in use, some of the equipment had to be modified and reconfigured in order to provide the necessary measurements. A detailed discussion later will include these modifications.

Because of the delicate nature of the measurements to be taken, it was deemed desirable to test equipment and procedures thoroughly in the laboratory prior to outdoor scintillation measurements of a one-way path versus a folded path. This was accomplished first in the 145-meter-long basement corridor of the Naval Postgraduate School's Spanagel Hall. The laser sources were placed at one end of the corridor and the detector and processing equipment were located at the opposite end. Additionally, a lab in the basement of Spanagel Hall was used to make some of the test measurements when a short range was necessary.

After satisfactory results were obtained in this controlled environment, the equipment was reconfigured in its

final form in the corridor of Spanagel Hall. This operation provided the final preliminary check prior to one-way versus folded path measurements in the field.

When these tests were completed, the equipment was relocated outside. Two outdoor sites were chosen. The first was the roof (sixth floor) of Spanagel Hall, which offered a reasonably realistic outdoor environment. For reasons to be discussed later, the equipment was then moved to a flat grassy area adjacent to and about 20 meters from Spanagel Hall.

B. DETAILS OF SCINTILLATION EQUIPMENT

The signal receiving and signal processing, or data reduction, equipment configuration remained unchanged during both phases of the experiment, while the optical and source configuration differed from the test phase to the measurement phase. A detailed description of the optical equipment in support of the test phase will precede an explanation of the optical equipment employed in the final configuration.

1. Optical Equipment

a. Test Phase

(1) Laser Sources. Two types of lasers were utilized as sources. One was a .6328 micrometer HeNe laser, model 155 manufactured by Spectra-Physics. The second, a GaAs 12 array laser was later modified using a mixer rod to obtain a uniform beam spot. Both lasers were mounted on

plates controlled by micrometer screw adjustment which aided in precision alignment.

(2) Triggering Equipment. A mechanical circular chopper connected to a 3000 rpm electrical motor provided modulation for the CW HeNe laser, and triggering for the GaAs laser and signal processing equipment. Two different choppers were utilized during the experiment. One had an open-to-closed ratio of 1:1 and the other of 1:4. The chopping frequency of both was 1000 Hz.

In order to establish a triggering pulse, synchronous with the optical pulses, a light emitting diode (LED) was positioned opposite a detector and the pair were mounted around the chopper to give a 1000 Hz trigger. This trigger pulse was used to trigger an Interstate P12 pulse generator set to create a 750 micro-second delay from the rise of the trigger to the GaAs laser trigger. The delay could be adjusted to obtain a proper interval between HeNe and GaAs pulses. The trigger pulse was also sent through a twin lead to a P25 pulse generator which initiated the triggering sequence for the data reduction system.

(3) Beam Splitter. A beam splitter was required to align the beam propagation direction from both laser sources along the same path. Several potential optical flats were tested; however, it was discovered that they created an unacceptable interference pattern. It was then

decided to use a 1.5 inch diameter NPC Pellicles which served as an excellent beam splitter.

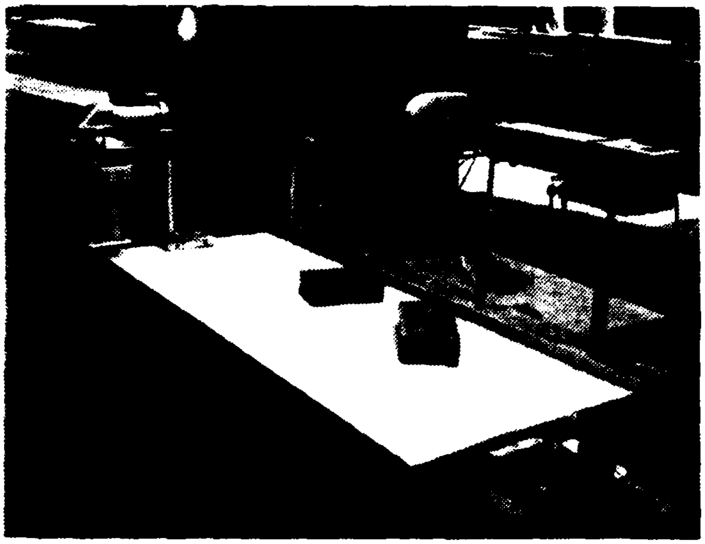
b. Measurement Phase

Dependent upon the system's geometry, either all, or a portion of, the equipment described below were utilized during scintillation measurements of a one-way path versus a folded path.

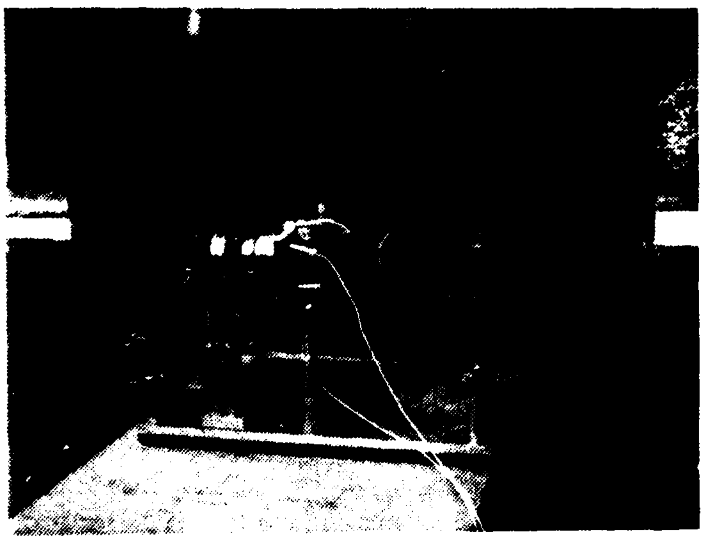
(1) Laser Sources. Both the one-way path and folded path sources were HeNe lasers with the same specifications as listed above. The folded path laser was modulated by the mechanical chopper while the one-way path laser was modulated by a Coherent Associates model 3003 Modulation system [Fig. 3). A Pockells cell, in conjunction with an external polarizer and a bias voltage, was employed to modulate the laser beam [Ref. 4].

(2) Beam Splitter. For the case of D = 0 (Fig. 1), (source and detector coinciding) two beam splitters were required. In all other measurements only one beam splitter was needed (Fig. 4).

The two main selection criteria for the beam splitters were the quality of optical flatness and size. They had to be large enough to accommodate the beam spot size so that there would not be an unreasonable degree of sensitivity in the alignment of the optical system. Several optical flats large enough for potential use were tested

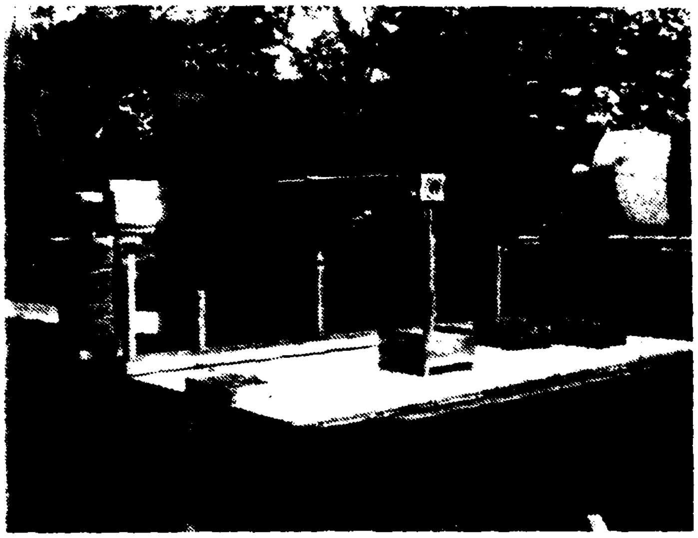


Source and Detector End Showing, from left, Detector, Beam Splitter, Chopper, Lens, Laser



Target End Showing, from left, Beam Splitter, Lens, Polarizer, Pockell's Cell and Laser. Mirror in back.

Figure 3. Source and Target Optics for D = 0



Detector End Showing, from left, Detector
with 3mm Aperture, Laser, Lens, Chopper

Figure 4. Source and Detector ($D \neq 0$)

for degree of optical flatness using an interferometer. Of those tested, a 6-inch diameter, 1-inch-thick fused quartz optical flat was selected as the target beam splitter and a 6-inch by 4-inch elliptical flat was selected for the detector beam splitter. Both were given an aluminum coating to provide about 50% transmission.

(3) Targets. Two targets, a flat mirror and an uncoated corner cube reflector were selected. The flat mirror, a 5-inch optical flat, was selected in the same manner as the beam splitter. The corner cube reflector had a 2-3/4 inch diameter.

2. Signal Detection Equipment

a. Telescope

During the test phase of the experiment, a 5-inch Celestron telescope with a focal length of 90 inches and a central obscuration was used to collect the energy.

An aperture of 3 millimeters was configured in front of the telescope in order to qualify the system as a point detector. Two criteria had to be met. The aperture had to be smaller than the fresnel zone size and the lateral coherence length ρ_o. The fresnel zone size in the corridor configuration was

$$\ell_F = (\lambda L)^{1/2} \tag{5}$$

For the corridor length of 145 meters, $\ell_F = 9.6$ mm for HeNe and $\ell_F = 11.5$ mm for GaAs. The lateral coherence length is given by Fante [Ref. 5] as

$$\rho_o = (1.45\ k^2 C_n^2 L)^{-3/5} \qquad (6)$$

From previous experiments [Ref. 3] in the corridor it was found that C_n^2 varies from 10^{-13} meters$^{-2/3}$ to 10^{-15} meters$^{-2/3}$. For the worst case, the lateral coherency length is 10.2 mm for HeNe and 15.7 mm for GaAs. Therefore the fresnel zone size was the critical parameter and an aperture size of 3 mm was chosen as being well within the limit for a point detector.

b. Detector

The detector utilized for the scintillation measurements was a Model 50 EHS Silicon Avalanche Detector manufactured by General Electric Company. This detector provided acceptable Signal-to-Noise ratios for both the GaAs and the HeNe lasers. A cavity that could be filled with liquid nitrogen surrounded the detector and its holder. Cooling allowed full utilization of the detector's capability to detect weak signals.

During the test phase, the detector apparatus was attached directly behind the telescope.

c. Preamplifier

The output of the detector was fed to a model 113 PAR Low-Noise Preamplifier. This provided high gain,

10 to 10^4, and adjustable High and Low Frequency Rolloffs that allowed selection of the bandwidth.

3. Signal Processing Equipment

Added to the data reduction equipment already in use was a second demodulator and Log Converter, a switch and two pulse generators. Modifications were implemented in the computer processing. These alterations resulted in a system (Fig. 5) capable of analyzing pulses separated by a few hundred microseconds, from two different sources.

a. Demodulator

After leaving the preamplifier, the two signals were passed to the demodulators (Fig. 6). These devices were triggered separately causing each to demodulate one of the signals.

An incoming signal pulse was held at its instantaneous maximum signal level in a flat topped pulse for a desired duration while this peak was sampled (Fig. 7). The background was then sampled and subtracted from the signal sample giving the differential output of the circuit.

b. Log Converter

Two Hewlett-Packard 7562 A Log Converters were the next instruments in the processing step. They produced dc output voltages proportional to the log of the dc input voltages (differential output of the demodulator).

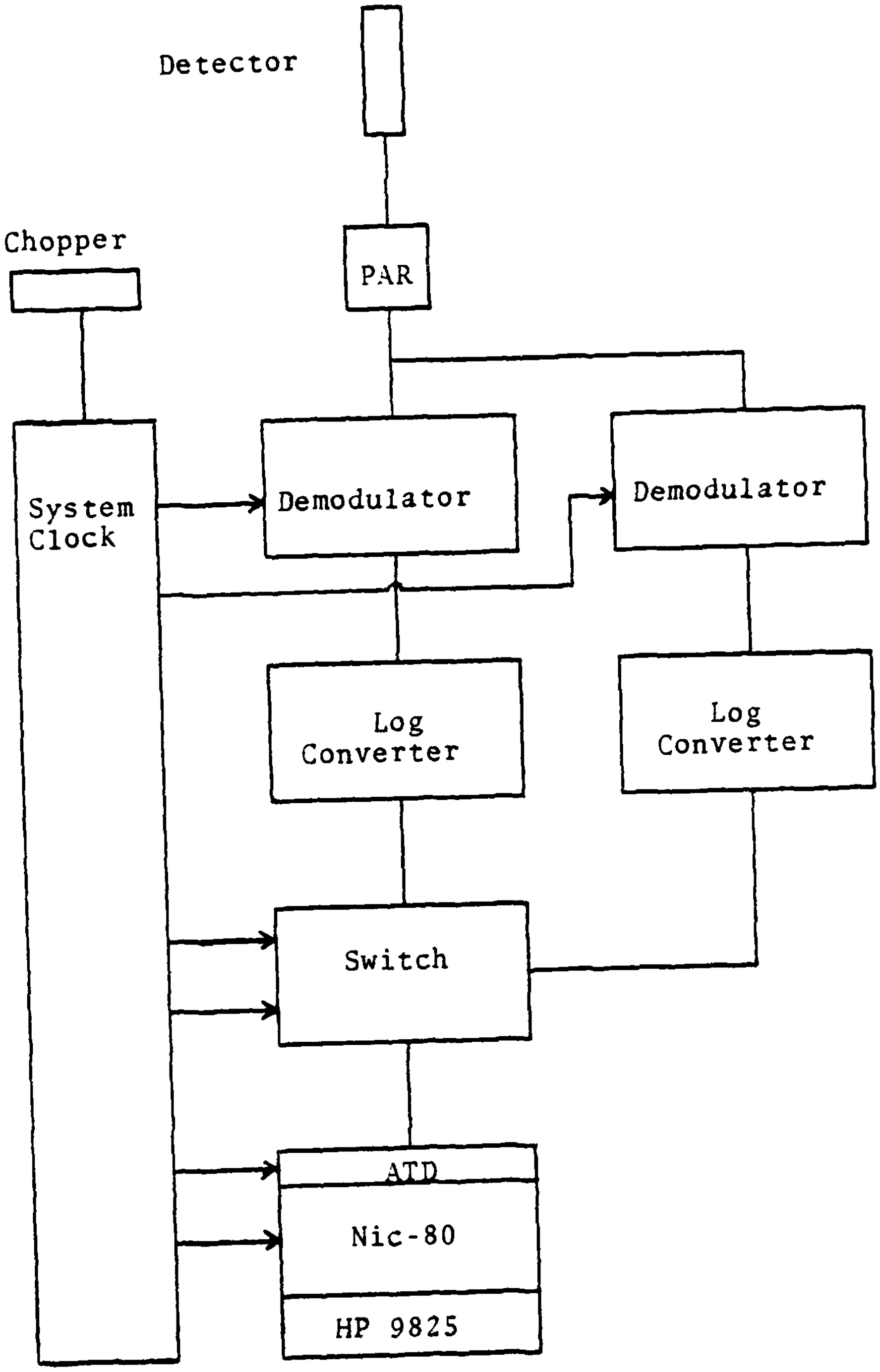


Figure 5. Diagram of Data Reduction System

Photograph Showing, from left, Nic-80, HP 9825 and HP 9871

On left from top: Demodulator, Switch, Log Converter, Pulse Generators, and Oscilloscope. On right from top: Log Converter, Demodulator, and Oscilloscope.

Figure 6. Signal Processing Equipment

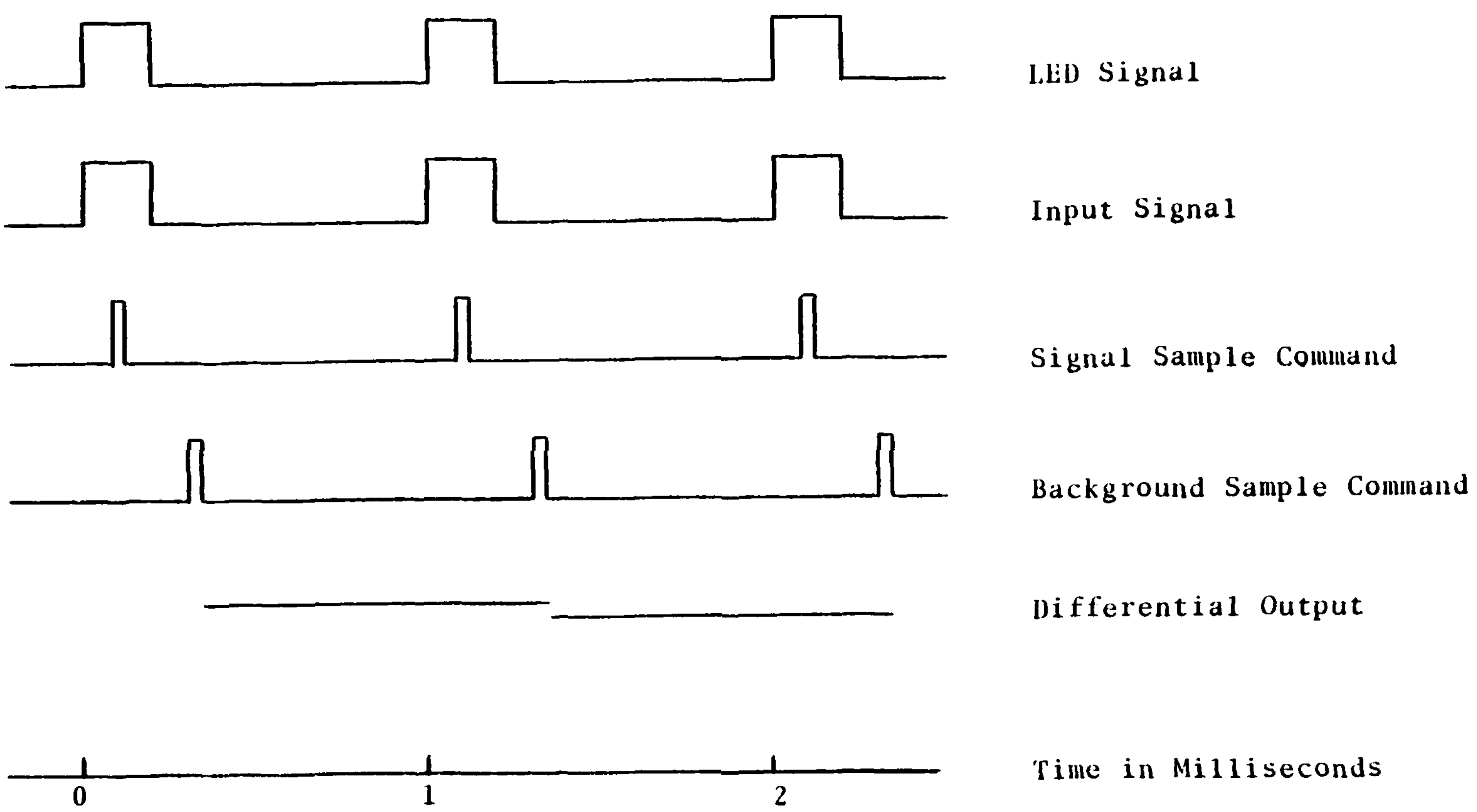


Figure 7. Diagram of Demodulator Waveforms

c. Electrical Switch

The most significant addition to the system, allowing the interlacing of the two pulses, was the design of an electrical switch based on an AD7510D1 analog switch powered by a 15-volt supply. The switch received control signals from the IEC P25 pulse generator along with the differential output signals from the two Log Converters. The trigger pulses, the compliment of each other, caused signals alternating between the two Log Converter outputs to be passed to the Nic-80 (Fig. 8) at a frequency of about 1000 Hz.

d. Nic-80 Data Processor

The next instrument in the sequence was the Nic-80 data processor manufactured by Nicolet Instrument Company. This is a data averager followed by a 12K 20-bit-word digital computer and a Tektronic CRT display unit. On-line data reduction by the Nic-80 provided a Gaussian shaped probability density curve from which the variance was calculated. Approximately, each 15 seconds, one value of the variance for each source was calculated from 16,384 samples. A detailed discussion of the Nic-80 can be found in Ref. 3.

e. Hewlett-Packard 9825

The HP-9825 functioned as the controller and input-output device to the Nic-80 and printer (Fig. 6). A direct interface between the Nic-80, HP 9825 and HP 9871 printer gave 16 pairs of variance values for the two sources during one run.

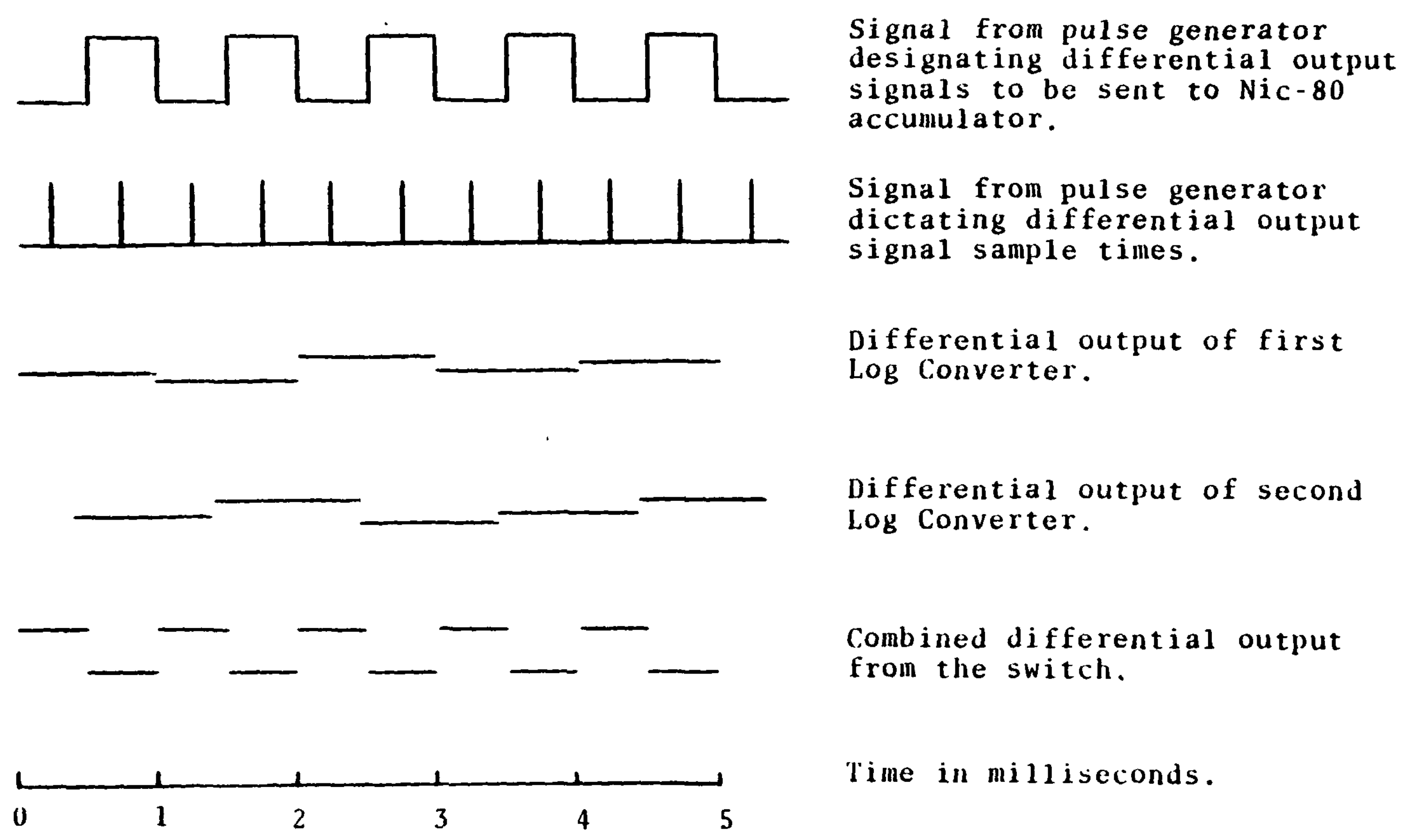


Figure 8. Interlacing of Output Signals

III. THE EXPERIMENT

A. EXPERIMENTAL GOALS

There were two main goals of the experiment. The main goal was to develop and test equipment and procedures to measure scintillation of two sources simultaneously. After the first was accomplished, measurements of the one-way and folded paths were to be taken varying the distance, D (Fig. 1), and compared with the theoretical predictions of Ze'evi [Ref. 2].

B. EXPERIMENTAL PROCEDURES FOR TEST PHASE

In addition to the main goal of testing equipment and procedures, several secondary objectives became apparent as the experiment progressed. Among these, the most significant was to compare the scintillation statistics of a coherent source with those of an incoherent source. Discussed in the following paragraphs are the sequence of experiments performed to arrive at a quantitative comparison of the two sources and to assure that the system was fully capable of producing the one-way versus folded path measurements.

1. 30 November 1981-1 December 1981

During this period the first experimental trials were performed in the basement corridor of Spanagel Hall using two laser sources, a HeNe laser and a GaAs laser. The lasers were aligned adjacent to each other with apertures about 70 mm

apart. A 3.0 mm and a 3.6 mm aperture were configured in front of the telescope separated by 70 mm, to collect the HeNe and GaAs beam's energy respectively. Both apertures were behind bandpass filters to reduce background light. Sixteen pairs of data could be taken during a run. However, at that time the data reduction system was limited to sampling each source for an entire 15 seconds so that after 30 seconds, one value for each of the two sources was calculated.

2. 9 December 1981

The previous trials were repeated with the addition of the electrical switch in the signal processing system. Inclusion of the switch refined the data reduction process by causing alternating source pulses to be sampled approximately every .5 milli-seconds. The pulses were separated by .35 milli-seconds, which according to Tatarskii [Ref. 6] is short enough to assume frozen atmospheric turbulence. At this stage, the signal processing configuration would remain the same throughout the remainder of the experiment.

3. 10-14 December 1981

The system was again refined, in this case to eliminate the effect of the path differences of the two sources. Reconfiguring the optical system as in Figure 9 produced beams from the two laser sources which propagated along identical paths. The NPC Pellicle was utilized for the beam splitter. To avoid aperture averaging, a single 3.6 mm aperture was placed in front of the telescope.

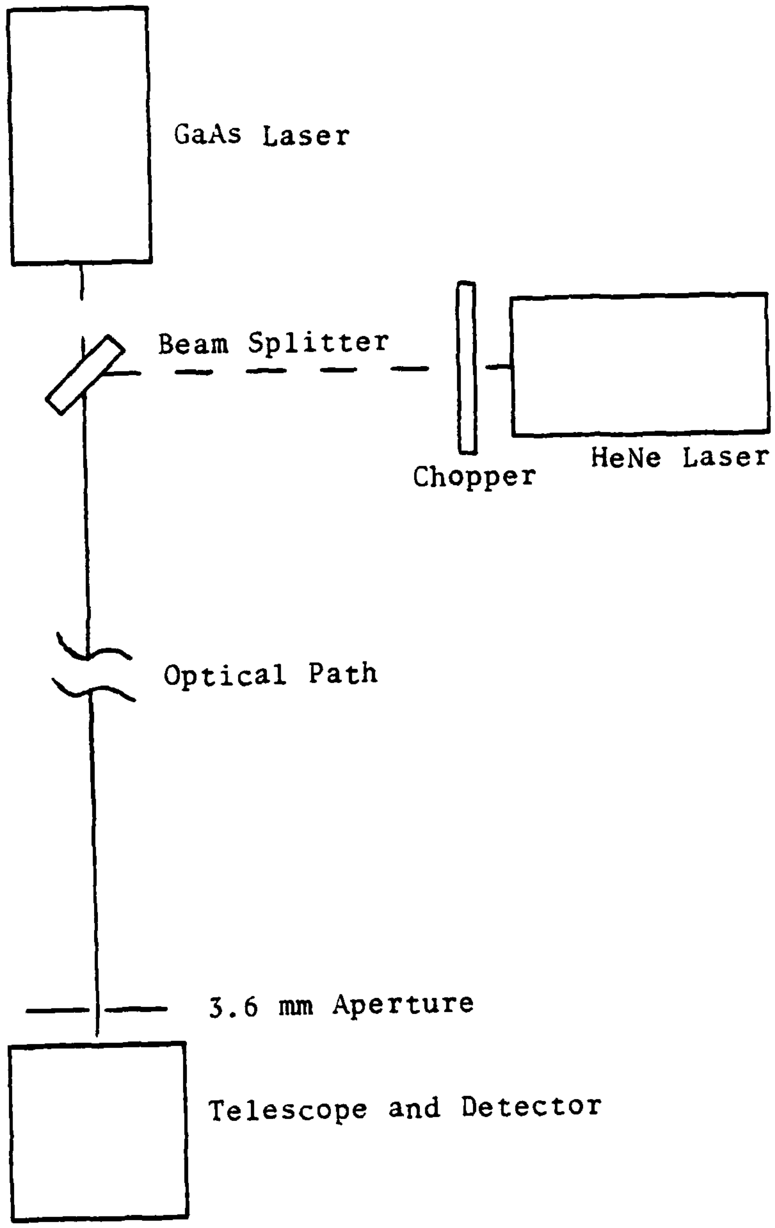


Figure 9. Diagram of Corridor System

In this configuration several measurements were taken to compare the scintillation statistics, the ratios of the variances given by equation 2, due to the turbulence in the corridor. Much of the corridor's turbulence was attributed to overhead heating ducts positioned along the entire optical path. Two major observations were made during these runs. First, as a function of time the values of variance from both sources did not follow the same trend. The GaAs laser variances remained fairly constant while the HeNe laser variance fell. Second, the GaAs variance values were very sensitive to minor adjustments in the laser alignment. Using an infrared viewer, a column of 12 rectangular patches was observed at a distance of 7 meters from the GaAs laser. Minor adjustments of the laser's micrometer screw changed the position of the patches relative to the HeNe spot by as much as an entire patch.

4. <u>18 December 1981-8 January 1982</u>

Because of the observations noted during the previous trials, it became necessary to investigate the possible contribution of the source variance to the variance of the intensity due to turbulence. The effects of turbulence were reasonably eliminated by shortening the optical path and relocating the equipment in a single room. The configuration was fundamentally as depicted in Figure 9 with the following exceptions. A source aperture of .33 mm diameter was placed in front of the beam splitter. The telescope was

eliminated and an aperture-to-detector distance of 2.35 meters was selected to resemble the focal length of the telescope so that the detector lens focused properly on the detector. The GaAs laser was aligned to allow the same patch as in the previous trial to fall on the detector. Neutral density filters were used to match intensities.

Several runs were taken in this configuration on six different days. Minor changes were made, such as increasing the beam splitter-to-chopper distance to reduce microphonic motion of the beam splitter. On the sixth day measurements were taken while alternating a neutral density filter in front of the detector to investigate the effect of different intensities on the value of the variances.

With the realization that the assumption of log normal distribution of the source intensity might be incorrect, it seemed more reasonable to assume a normal distribution and therefore bypass the Log Converters in processing the signals. Runs taken in this configuration included a new 400-watt GaAs laser with a mixing rod.

5. <u>12-13 January 1982</u>

After the source variances had been determined, the optical system was again arranged along the corridor to measure the correlation and ratios of the variances of HeNe and GaAs lasers. During this and all further measurements, the GaAs laser with mixer rod was used because it provided a beam of uniform intensity. An aperture of .5 inches was

positioned along the propagation path seven meters from the beam splitter. The second chopper (open-to-close ratio of 1:4) provided a means to sample the two pulses within .2 milli-seconds of each other during one cycle.

6. <u>14 January 1982</u>

Previous trials had given inconclusive correlation results; therefore it was desirable to determine if the atmosphere was frozen during the interval between pulse sampling. This was accomplished with a single HeNe laser whose beam passed through a modified 1:4 ratio chopper. A 2.2 mm hole drilled 1/3 of the distance after each opening in the chopper modulated the laser, giving two pulses separated by .27 milli-seconds each cycle.

7. <u>18-22 January 1982</u>

The previous experiment was repeated with the GaAs laser. Two consecutive pulses, separated by 2.6 milli-seconds were obtained by using the double pulse mode of a pulse generator. A modification was applied to the demodulator previously employed in the HeNe signal circuit to accommodate the peculiar pulse stretching requirements of the GaAs pulse. Both this and the previous experiment yielded excellent results.

8. <u>Week Beginning 25 January 1982</u>

Having obtained conclusive results in the two previous experiments, correlation measurements were once again initiated with two different sources. The configuration shown in Figure 9 was modified to include a 3 mm aperture in front of the GaAs laser, added to approximate a point source.

During this trial and the double-pulsed GaAs laser trial a bias voltage of 1.5 volts was applied to both demodulators. The demodulators were designed to operate with only positive signals; however, it was found that the PAR AC coupling which shifted the zero of the signal to the average value across one cycle resulted in signals with negative values. Higher signals gave higher negative values after passing through the PAR. To investigate the effect of this phenomenon, several measurements were taken while varying the bias voltage to the demodulators between -0.5 volts and 2.5 volts. It was found that negative signals gave erroneous results.

9. 2-3 February 1982

The above trial was repeated substituting a second HeNe laser for the GaAs laser. The purpose of this experiment was to determine if the correlation between two different HeNe lasers was high enough for use in the one-way-versus-folded-path measurements. Signal pulse widths were adjusted to .20 milli-seconds and .25 milli-seconds for the chopped and electrooptically modulated lasers respectively. Approximately .35 milli-seconds separated the pulse sampling. Prior to taking measurements in this configuration the problematic demodulator's circuitry was modified to eliminate the requirement for a bias voltage.

10. 4-11 February 1982

Upon satisfactory completion of equipment testing, the systems final configuration (Fig. 10) for one-way-versus-folded-path measurements was arranged in the corridor. The purpose of this trial was to test the system in a controlled environment prior to taking the measurements outside.

Figure 11 depicts the optical system configured for the case of D = 0 (Fig. 1). Initially the Pockells cell modulated laser (one-way source) was positioned perpendicular to the optical path. However an interference pattern was induced by double reflection from the front and back surfaces of the six-inch beam splitter. To resolve the problem the polarization of light was adjusted to be in the plane of incidence so that the Brewster's angle given by Hecht and Zajac [Ref. 7] as $\tan \theta_p = n_t/n_i$ could be set to eliminate the reflected beam from the front (uncoated) surface. For air $n_i = 1.0$ and for fused quartz $n_t = 1.458$ [Ref. 8] giving an angle of 55.6°.

Five scintillation measurements were taken with a flat mirror target while varying detector aperture sizes, from the detector lens decreasing to 3 mm. During runs with smaller apertures, the detector was cooled with liquid nitrogen and an avalanche voltage of 1600 volts applied. Ratios of the average variances of the folded path to the one-way path for each case were calculated. These results

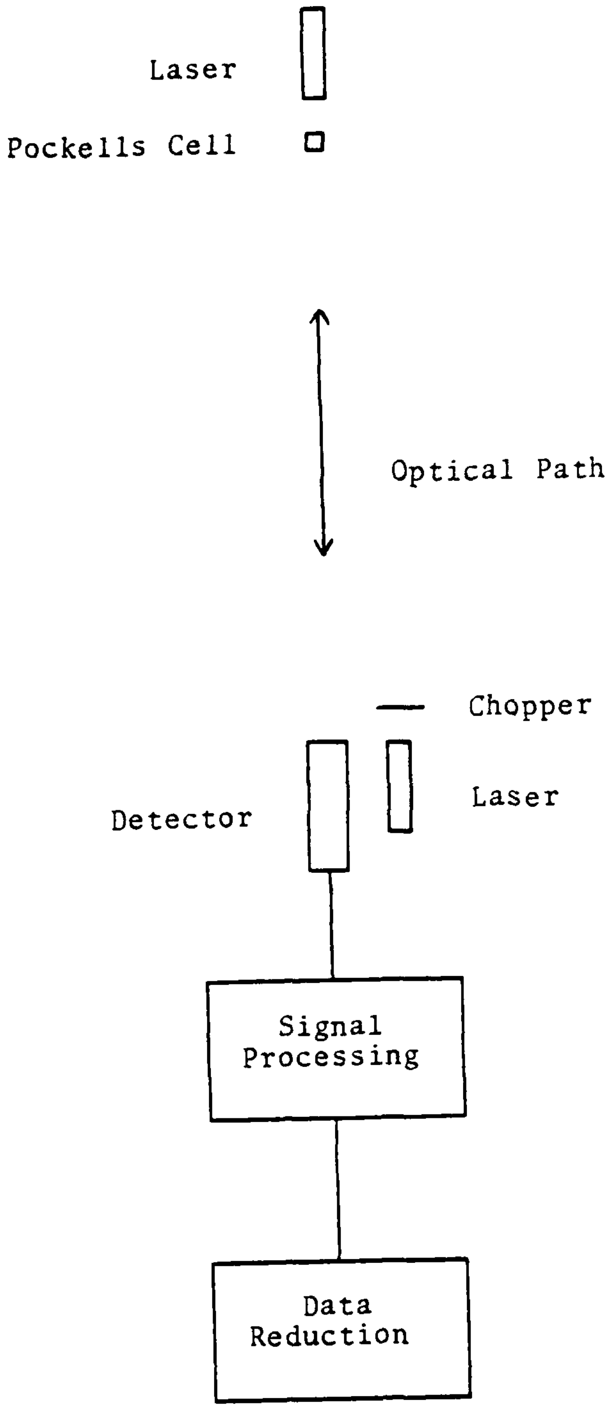


Figure 10. System Diagram for Scintillation Measurements

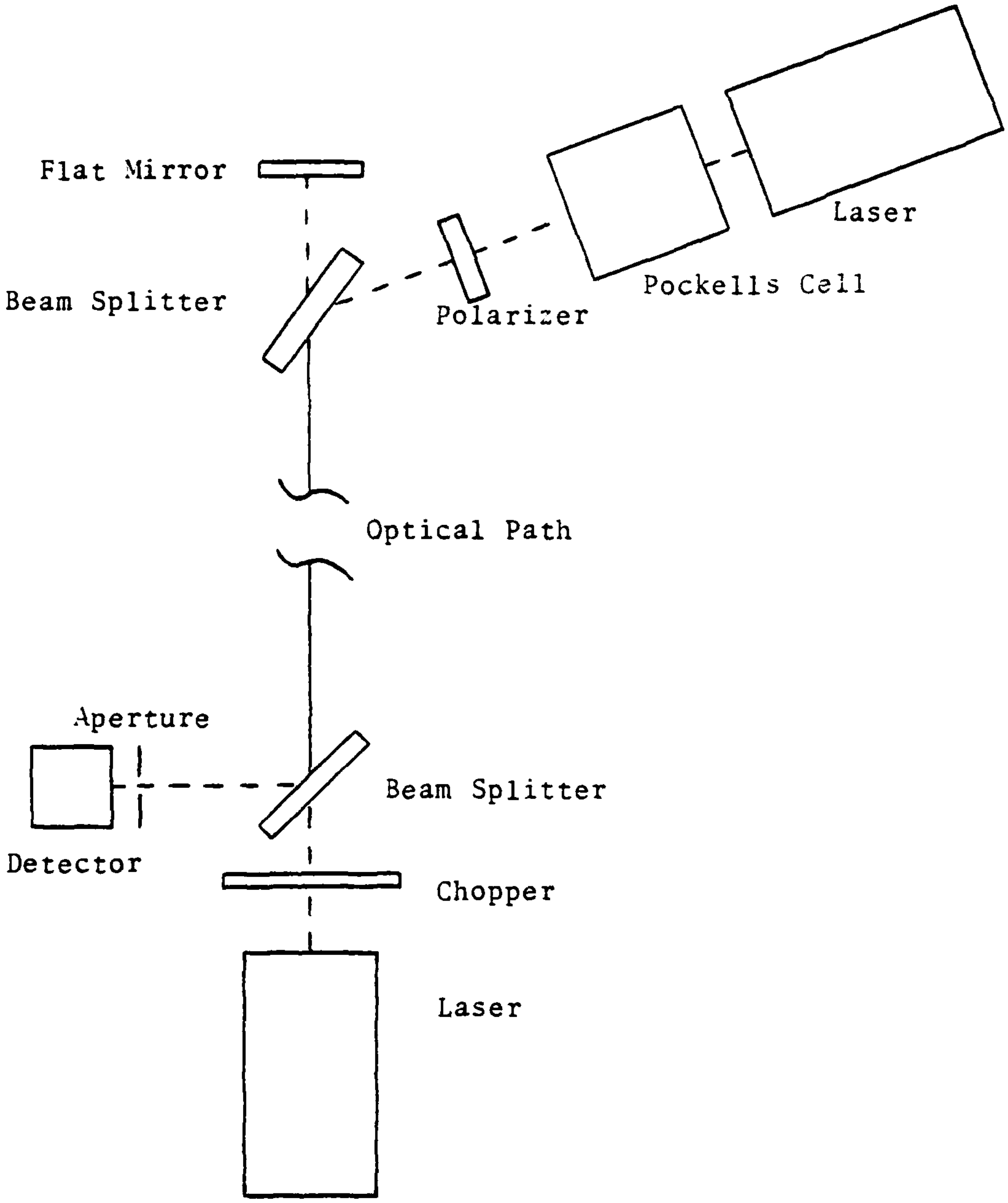


Figure 11. Diagram of Optical System

gave quantitative experimental information on the effect of aperture averaging. Additionally, a set of measurements were taken with the retro-reflector as a target.

C. EXPERIMENTAL PROCEDURE FOR MEASUREMENT PHASE

With confidence gained in equipment and procedures, the system was relocated from its controlled environment to outdoor sites. All outside system configurations were for one-way-versus-folded-path (Fig. 10) scintillation measurements. The objective of this phase was to obtain variance measurements of the folded and one-way paths for detector-source separations ranging from one meter to an exact folding (D = 0). The following paragraphs describe the sequence of events leading to the collection of this data.

1. Week Beginning 15 February 1982

The roof of Spanagel Hall was selected as the first measurement site because it offered a flat uniform surface without obstructions, reasonably uniform turbulence across the optical path, close proximity to support facilities, and a convenient power supply. The specially designed optical benches (Fig. 3) were set on heavy cement tables positioned 60 meters apart. These were used to minimize small external vibrations. A room on the roof approximately 20 meters from the detection equipment sheltered the signal processing equipment.

Initially, measurements were attempted during hours of darkness for ease of efforts in the critical alignment process. However, two weather factors prohibited the collection of meaningful data. Nights tended to be foggy which resulted in some uncertainties in the data. The second factor, low turbulence levels, gave variance values in the source variance regime of 10^{-4}.

Since the above factors could not be regulated it was decided to attempt measurements during daylight. Data collection was initially hampered by equipment difficulties. First, the triggering signal from the LED-Detector pair was extremely distorted because of the large amount of ambient light that reached the detector. This problem was eliminated by encasing the entire chopper and contents in an aluminum box. The second difficulty was similar to the first in that the ambient light reaching the Silicon detector caused unacceptable noise levels. A narrow bandpass filter inserted in front of the detector completely eradicated the noise signal. Upon implementation of the above system additions, scintillation measurements for the cases of exact folding ($D = 0$) and with a separation distance of 5 cm were taken. Both the flat mirror and corner cube reflector were used as targets.

Data taken thus far was somewhat erratic. An investigation of the possible basis for this revealed that high winds

of about 15 knots created small vibrations in some of the optical elements leading to erroneous scintillation measurements. Attempts to isolate the elements from the wind proved fruitless.

2. 25 February 1982-4 March 1982

The factor of the wind's influence on the roof necessitated selection of a second site. An area adjacent to and approximately 20 meters from the southern side of Spanagel Hall provided an adequate optical range. The cement tables were stationed with a separation of 62 meters. A flat grassy area with a concrete sidewalk crossing about midway comprised the terrain over which the laser beams propagated. A portion of the optical path was shaded by a few trees located from 10 to 100 meters from the path. The roof configuration of the optical and detection system was again employed with the optical elements located 1.1 meters above the ground. A room in the basement of Spanagel Hall housed the signal-processing equipment.

With a 3 mm detector aperture, measurements were attempted using both the retro-reflector and flat mirror as targets. These runs included source-detector distances of 0 and 5 cm. Although data collected with the retro-reflector target seemed to be consistent, the flat mirror target again resulted in erratic data. Night observations at the detector of the folded path beam spot revealed a great deal of

structure. It was observed that this effect was caused by minor inhomogeneities within the six-inch beam splitter. In order to eliminate this problem, the system was again reconfigured with the flat mirror removed and the six-inch beam splitter with its coated surface oriented toward the detector, substituted for the target (Fig. 12). This arrangement included direct alignment of the one-way source and detector. A second check of both source beam spots showed that neither exhibited the structure discovered earlier.

One further addition was made to the optical system prior to taking final scintillation measurements. To reduce the problems of beam wander and sensitivity of the system to alignment, plano convex lenses with focal lengths of 285 mm were placed directly in front of both lasers to diverge the beams. A beam spot of sixe 22 cm was obtained at 62 meters, compared with 7 cm without the lenses.

These final system corrections proved to be sufficient to permit scintillation measurements to be taken. An acceptable signal-to-noise ratio was achieved by applying the avalanche voltage of between 1900 volts and 2000 volts (1600 volts when the detector was cooled) to the detector and adding gains from 200 to 1000 from the PAR. Although several runs were taken for each of the five detector-source separation distances (D), 16 data pairs could be used for each distance. The criterion of precise optical alignment had to be met for meaningful data to be collected. Judgments on the

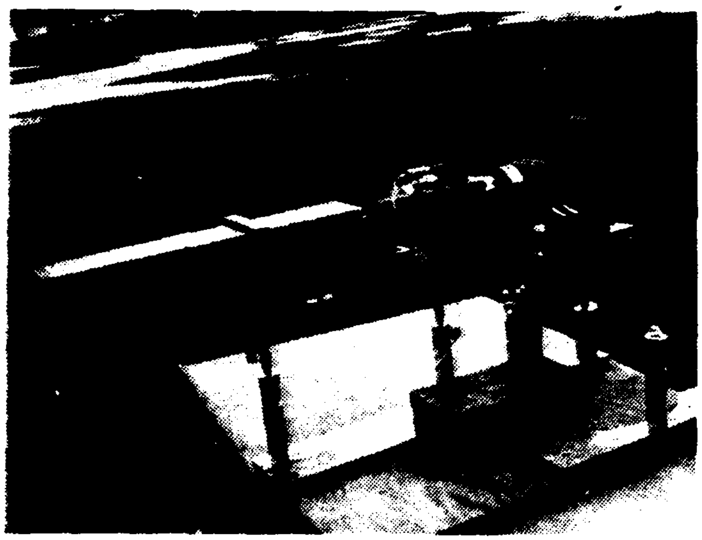


Photo showing, from left, Laser, Pockells Cell, Polarizer, Lens, 6" Beam Splitter (Target)

Figure 12. Final Target Area Optics

acceptability of the data were easily made by viewing the CRT display of the Nic-80 during on-line data reduction. As discussed in Section II, a Gaussian shapped probability curve was displayed on the CRT for each data point. During runs lacking the precise alignment required, obvious distortions in the shape of the Gaussian curve occurred. Major inconsistencies were also found among the 16 data pairs colle[illegible] during one of these runs.

However, with patience and extreme care in aligning the optics, five sets of acceptable measurements were collected on three separate days. The results of data collected during this experiment and on some of the previous trials are reported in Section IV, Results and Conclusions.

IV. RESULTS AND CONCLUSIONS

A. GENERAL

As was stated earlier, the two major goals of this experiment were to test the equipment and procedures and to compare scintillation measurements for one-way and folded paths. The measurements can be broken down into two distinct experimental evolutions. First is a group of experiments beginning with the 30 November 1981 trial, that measured one-way optical path scintillation. The second category of data collection consists of the 25 February 1982-4 March 1982 experiment and those directly leading to it that included both one-way and two-way experiments. The results of the work will be discussed within the framework of these two categories. The discussion to follow will demonstrate how the evolution of results gave credence to the outcome of the final three days' measurements.

B. ONE-WAY MEASUREMENTS

The primary quantitative measure used in analyzing the one-way variance data was the principle of Least Squares curve fitting. A slope and ordinate intercept were obtained from a straight line drawn through the data points. From data read into a Hewlett-Packard 85 calculator using its "Standard Pac" cartridge, the equation of the line was determined:

$$y = ax + b \quad (7)$$

where y = Value of the ordinate variance,

x = Value of the abscissa variance,

a = Slope of the line,

b = Ordinate intercept.

Also obtained from this program was the correlation coefficient, r, of the data.

1. Correlation Measurements Prior to 18 December 1981

Of the numerous measurements made with the GaAs and HeNe lasers together, ten sets of runs were chosen for linear regression computations. The HeNe and GaAs variances were designated as the ordinate and abscissa points respectively. Eight of these gave slopes between .92 and 1.28 while the remaining two were 1.87 and 1.73. Correlation coefficients ranged from .71 to .96 with all but one of the ten below .90. A calculated slope of approximately 1.518 (from Equation 2) and a correlation equal to or greater than .95 was expected for selection of these two sources for the folded path measurements.

After searching for a reason for inconclusive results at this stage, it was felt that, due to the time varying inconsistencies in the variance values as discussed in Section III, one or both of the sources were unstable and could have contributed to the atmospheric turbulence variance. Generally it is expected that the laser source variance is much less

than the variance due to the atmosphere. If this were not the case for the HeNe laser, and the two variances were additive, a slope of less than the expected 1.518 would occur and thus explain most of the data. Additionally, unstable laser sources could result in lower correlations than expected.

2. Source Variance Measurements

Approximately 80 measurements, each consisting of 16 pairs, were produced in the short-range experiments with the assumption of log normal distribution. Three of the results are summarized below. First, both laser's instabilities grew with time. For example, during one three-hour series of runs the GaAs laser variance grew by 21% while the HeNe laser variance grew by 35%. Second, at low signal intensities (less than about .7 volts) the variance of the HeNe laser had very high values. Third, a definite intensity dependence of the source variance of both lasers was discovered.

This last result led to a change in the log normal assumption to an assumption that the source variances were normally distributed. A brief mathematical explanation of the difference in the two assumptions is found in Appendix A. By extracting the average intensity values from the Nic-80 and bypassing the Log Converters, the values of the variance of the normalized intensity (Appendix A) were calculated

for six sets of runs on 8 January 1982. The values (Appendix B) of the normalized intensity variance for the GaAs laser (with and without mixer rod) demonstrated that for each pair of measurements, higher average signals resulted in lower variances. Values for the HeNe laser were too close to show the same intensity dependency. The HeNe source variances were all less than 3.0×10^{-4} while the GaAs source variances ranged from 4.6 to 7.8×10^{-4}.

3. Single Laser Correlation Measurements

In testing the frozen turbulence assumption, conclusive results were obtained with both the GaAs and HeNe lasers with a pulse sampling separation of approximately .50 milli-seconds. Measurements with the double pulsed HeNe laser gave an excellent correlation of .998, a slope of 1.01 and ordinate intercept of -2.74×10^{-4} (Fig. 13). Similarly, data taken for the double pulsed GaAs laser revealed a correlation of .999, a slope of 1.04 and an ordinate intercept of -2.42×10^{-4} (Fig. 14). The calculated slope in both cases is a 1.0 (Equation 7).

4. Two Source Correlation Measurements

Data collected during the week of 25 January 1982 served the purpose of investigating the effect of applying different bias voltages to the demodulators in an attempt to maximize the correlation of variances between the GaAs and HeNe lasers. From the summary of data collected on

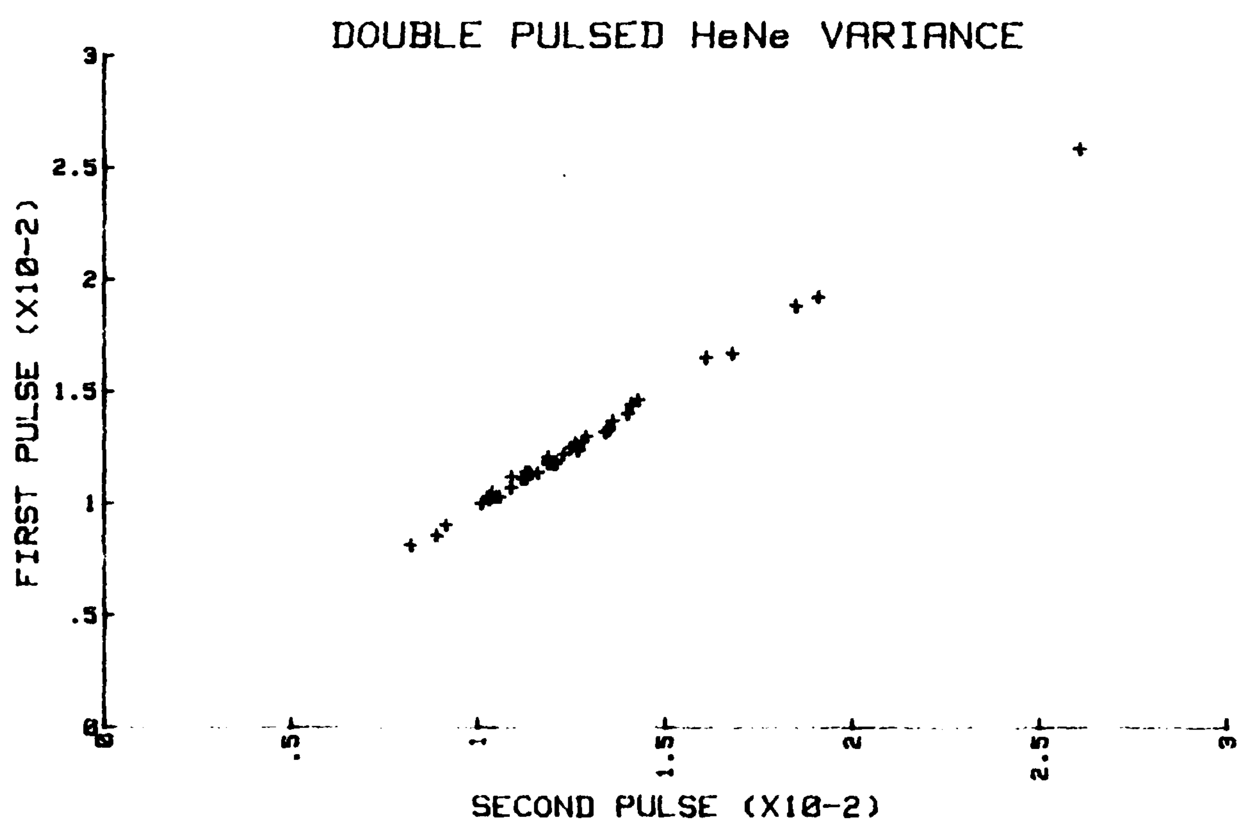


Figure 13. Graph of Linear Regression for Double Pulsed HeNe Laser

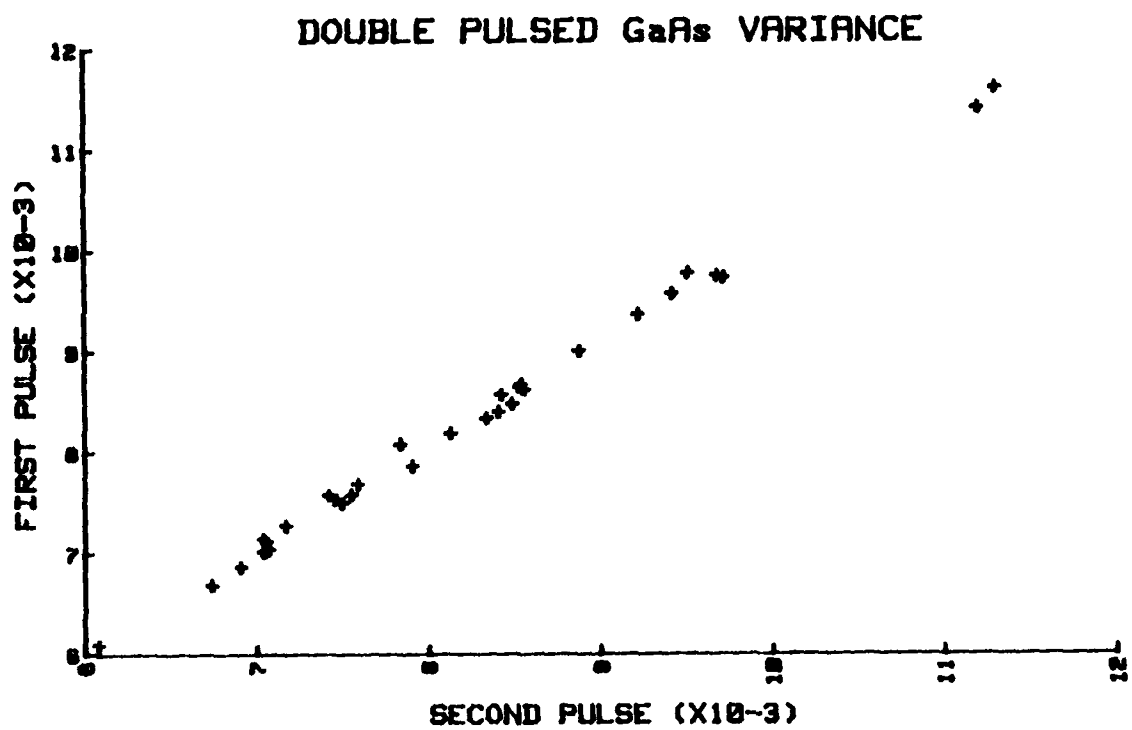


Figure 14. Graph of Linear Regression for Double Pulsed GaAs Laser

26 January 1982 (Appendix B), it is seen that except for one case, increasing the bias voltage increased the correlation. A repeat of run number 5 the following day yielded results that also supported this trend. For the case of a bias voltage of 2.5 volts, a correlation of .973, slope of 1.673, and ordinate intercept of -6.25×10^{-3} was achieved (Fig. 15).

The best measurements taken of five runs conducted using two different HeNe lasers yielded a correlation of .996, slope of 1.137, and ordinate intercept of 1.90×10^{-3} (Fig. 16).

Although the results quoted above are for the best data in each series of runs, the overall correlation coefficients for the two HeNe sources' runs were slightly higher than those of the HeNe and GaAs source runs. It was also noted that in both cases the experimental slope values were slightly greater than 10% higher than the theoretical values.

C. FOLDED PATH MEASUREMENTS

The results of scintillation measurements of a folded path versus a one-way path, taken in the three different locations, will be discussed. It must be pointed out that there is a degree of uncertainty in the confidence of the results of the first two experiments because of the structure discovered in the six-inch beam splitter. However, they will be discussed to the degree in which they relate to the final results and to show general trends.

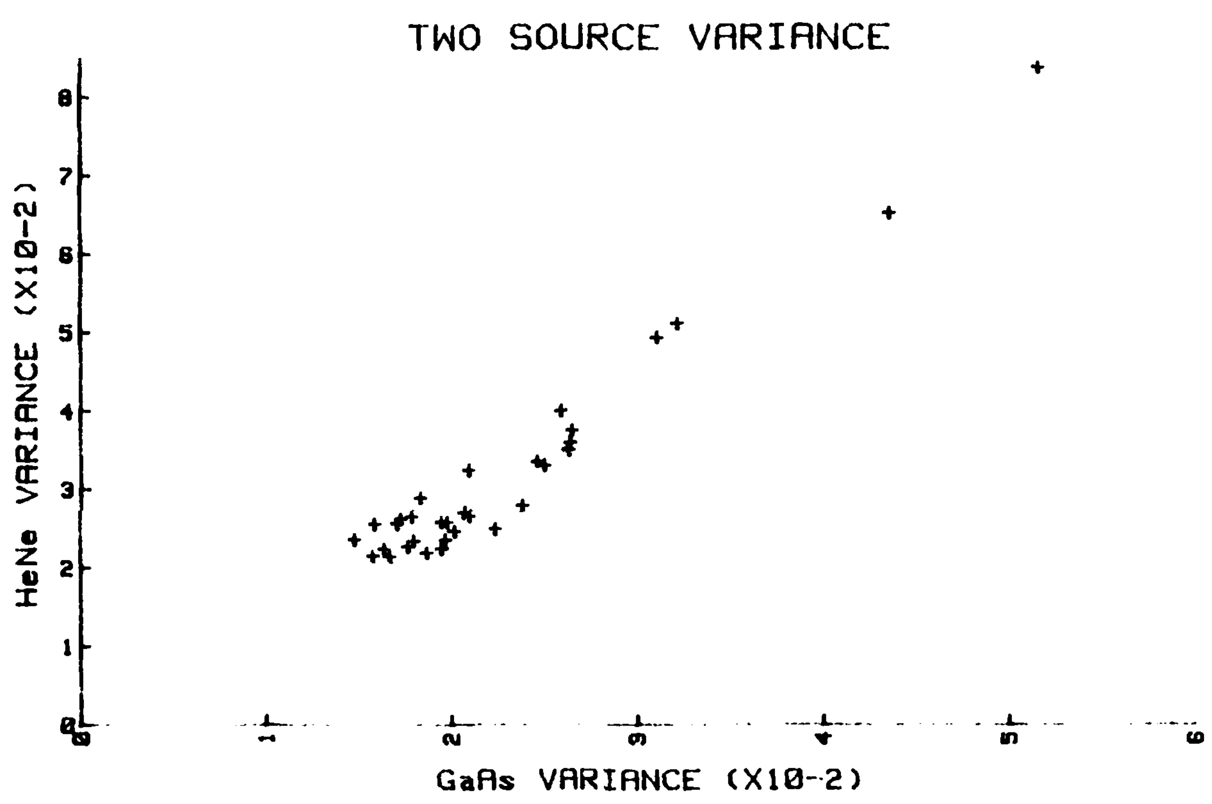


Figure 15. Graph of Linear Regression for HeNe and GaAs Lasers

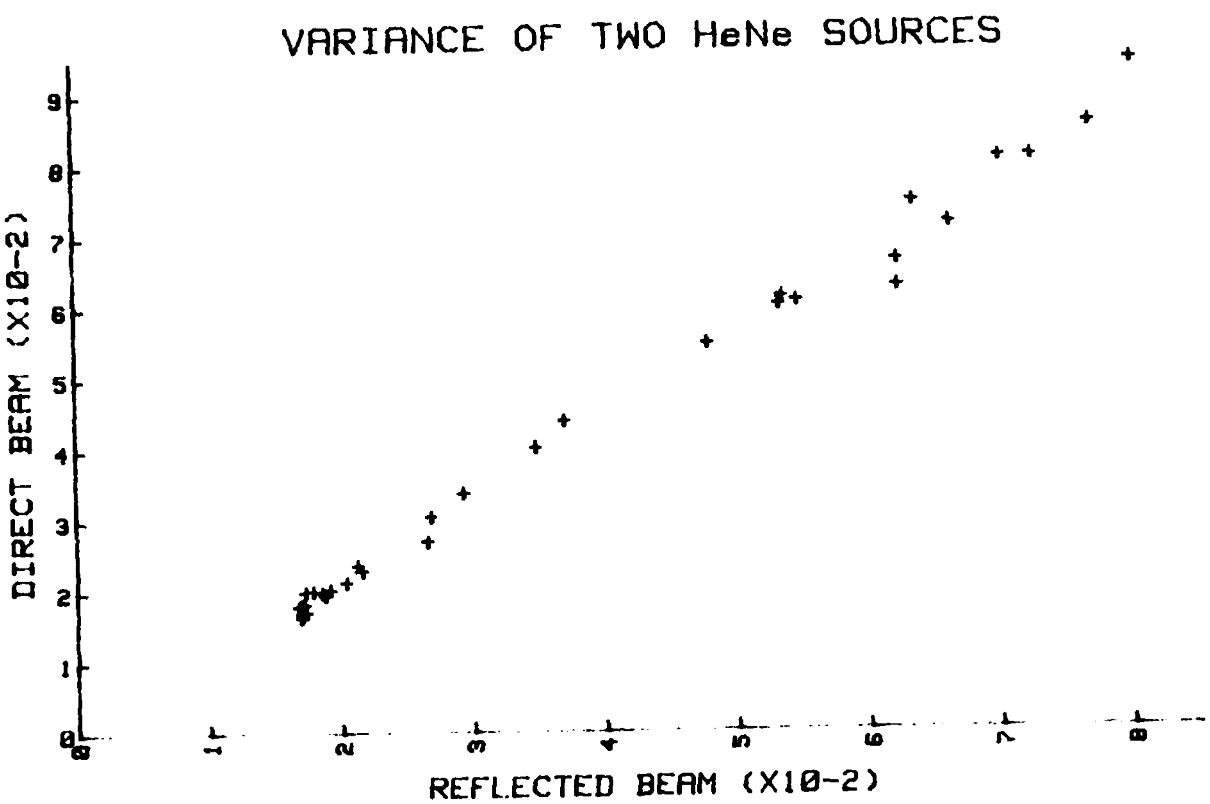


Figure 16. Graph of Linear Regression for Two HeNe Lasers

The quantitative measure used in analyzing the data collected during this phase was the ratio of the averages of the scintillation strengths of the folded path and one-way (single path) given by

$$R = \frac{<\sigma_F^2>}{<\sigma_S^2>} \qquad (8)$$

According to Ze'evi's theoretical prediction [Ref. 2], for the case of spherical waves, this ratio can be expressed as

$$F = 2^{11/6} \; [1 + f(y_o)] \qquad (9)$$

where y_o is given by equation 4. For example, in the exact folding case $y_o = 0$ and $f(y_o) = 1$ (Fig. 2). Therefore a ratio of 7.13 is expected. For different values of the source-to-detector distance, D, and a selected value of L_o, the theoretical curve can be compared with experimental data.

1. Corridor Measurements

A single series of five measurements demonstrated the effects of aperture averaging. For the one-way path, the lens aperture resulted in a variance of 1.48×10^{-2} while the 7 mm, 6 mm, 4.3 mm, and 3 mm apertures yielded a fairly constant value of approximately 2.50×10^{-2}. As was discussed previously, this was expected. However, the folded path variances increased from 3.50×10^{-2} to 19.98×10^{-2}

with decreasing apertures. Ratios (R) thus increased from 2.43 to 8.61. According to Ze'evi [Ref. 2], the curve illustrated in Figure 17 should flatten out around the 3 mm point. Because insufficient energy reached the detector with smaller apertures, this could not be experimentally verified.

One set of 40 data pairs with the corner cube reflector as the target yielded a ratio of 3.71.

2. Roof Measurements

Although scintillation measurements were taken for both the cases of exact folding and for a 5 cm detector-to-source separation distance, only the results of the exact folding are reported. Three consecutive runs of 16 data pairs each, with the flat mirror target yielded ratios of 8.19, 5.70, and 6.26. Weather conditions during the first run were clear and sunny; however fog began to settle in during the latter two. Ratios of 2.55, 3.92, and 2.92 were recorded for three consecutive runs with the retro-reflector target.

3. Final Measurements

Immediately prior to implementing the final configuration as depicted in Figure 12, scintillation measurements using the retro-reflector target for the case of exact folding were obtained. The resulting ratios for two runs were 3.44 and 3.83.

Results of data collected during final configuration runs appear in summarized form in Appendix B. Measurements

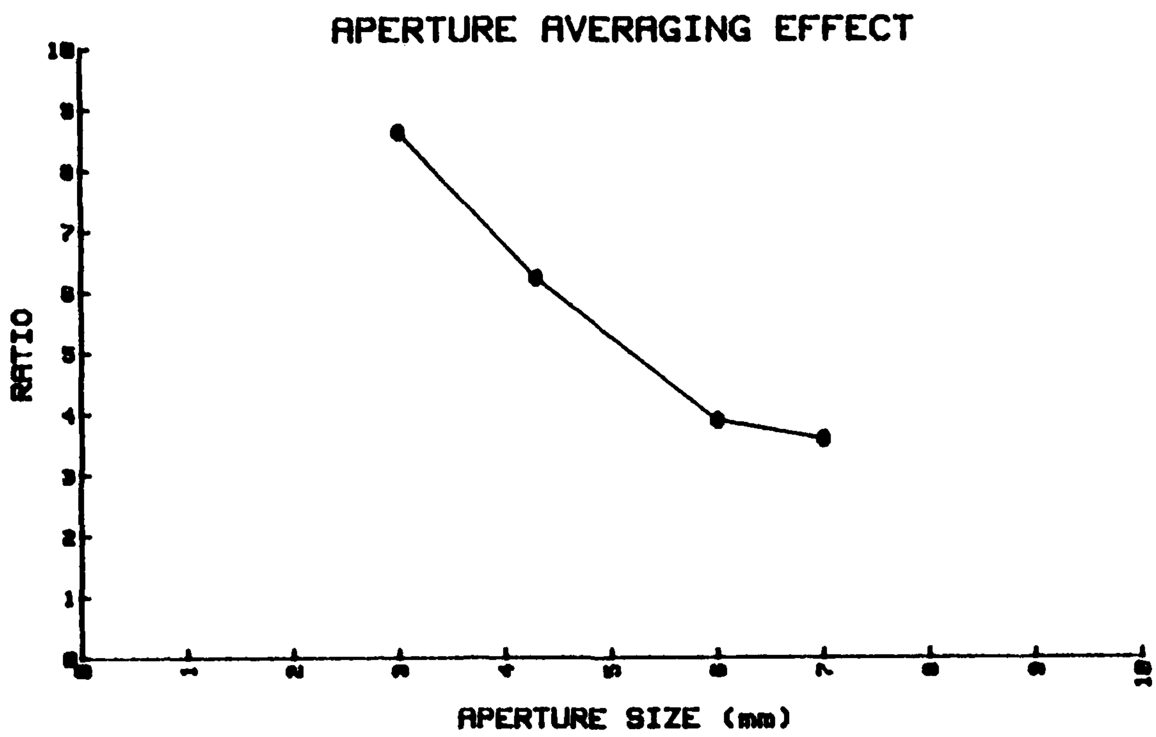


Figure 17. Graph of Aperture Size versus Variance Ratio

with detector source distances of 0, 20, 40, 70, and 105 centimeters yielded ratios of 8.23, 6.19, 6.12, 4.35, and 3.22 respectively. One ramification of data collection throughout a three-day span during different periods of day was variances that ranged from 9.20×10^{-4} to 1.48×10^{-1}. An outer turbulence scale size (L_o) of 20 cm gave the best fit of the theoretical prediction (equation 9) to the experimental results. Figure 18 shows y_o (equation 4) plotted as a function of both the theoretical ratio (the solid curve) and the experimental points.

Of the 80 data pairs collected during the above five runs, there were six instances in which an individual data pair yielded a ratio differing by a factor of two from the average ratio for that particular run. Ratios of the majority of the remaining data pairs were within 25% of the averages. The run with the most consistent data was for the case of exact folding while the most inconsistencies occurred in the D = 20cm and D = 40cm runs. There are two known possible sources of error. The first is alignment. Precise alignment was the most demanding and difficult requirement of the experiment. The second was the apparent influence of temperature on the functioning of the Pockells cell. Occasionally the average one-way signal strength would change by as much as 20%. After this occurred, a check of the modulation system revealed that a different bias voltage to the

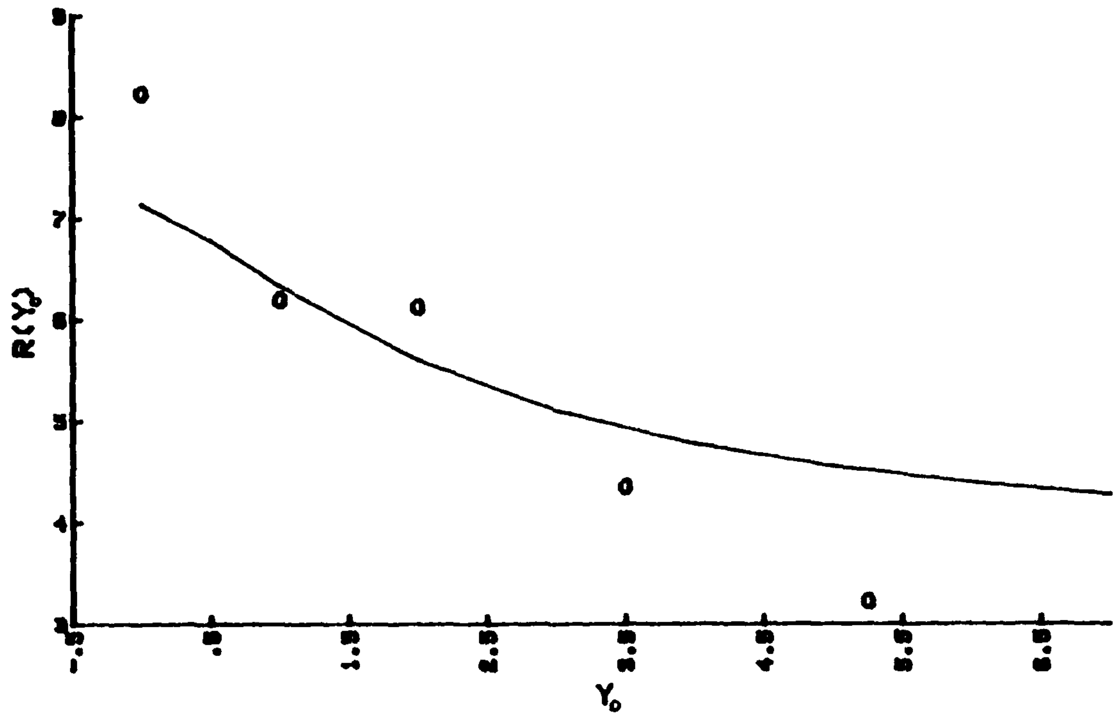


Figure 18. Graph of Y_o versus $R(Y_o)$

Pockells cell was needed. As mentioned in Section III, the data's acceptability was judged by the shape of the Gaussian curves. One such set of curves for the twelfth data pair in the exact folding case is given in Figure 19.

D. CONCLUSIONS

It seems reasonable to draw five main conclusions from these results.

First, it is experimentally feasible to measure scintillation strength along a one-way and folded path and to vary the detector to source distance with the equipment available.

Secondly, the turbulence must be great enough to yield variances of at least 10^{-3} to avoid significant contributions from the HeNe sources utilized in this experiment.

Thirdly, the assumption of frozen turbulence is correct for sampling times of .30 milli-seconds.

Fourthly, a ratio of the variances of the folded path to one-way path for the corner cube reflector target and exact folding is of the order of 3.44.

Fifthly, there is a relationship between the normalized log intensity variance over a folded path and one-way path, and the system's geometry which is consistent with Ze'evi's model.

The latter two items require further investigation. The second item must be checked for each laser.

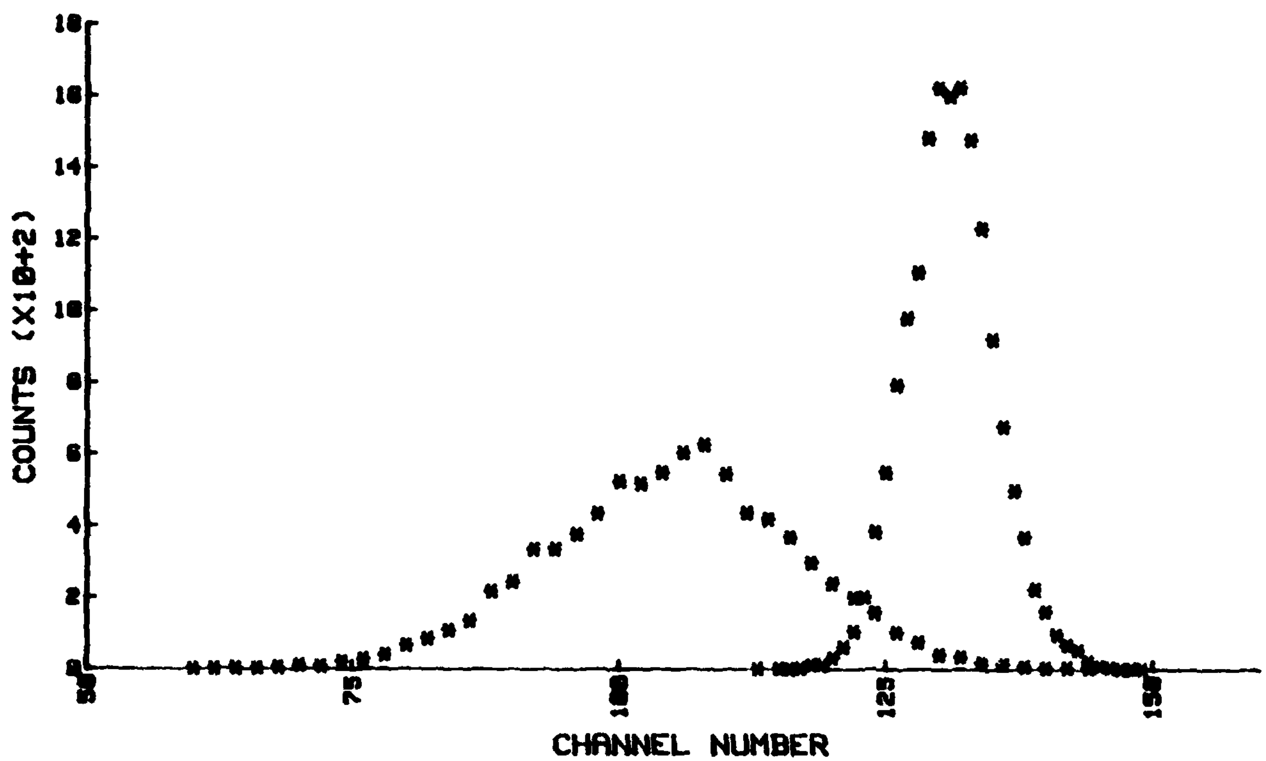


Figure 19. Graph of Gaussian Shape Probability Curves for Folded (Wide Curve) and Single (Narrow Curve) Paths

V. SUGGESTIONS FOR FURTHER INVESTIGATION

The following is a compilation of miscellaneous recommendations for future experiments.

A broader data base should be obtained for the one-way-versus-folded-path scintillation statistics. Measurements should include data points for 5 cm or 10 cm intervals of the source-to-detector distance and should be taken at a variety of field locations. Initially this should be with equipment employed for this experiment.

The effects of aperture averaging for the one-way-versus-folded-path case should be experimentally verified. This can be accomplished by using shorter ranges to increase the energy reaching the detector, thereby permitting smaller detector apertures to be tested.

Further investigation into the scintillation statistics of a one-way versus folded path, using a corner cube reflector target should be conducted. A modification of the optical system or the procurement of a high quality beam splitter to replace the six-inch beam splitter in the current optical system would be required.

The basic experiment could be repeated using different laser sources (both coherent and incoherent). A purpose of these experiments is to determine the extent of applicability of the theoretical predictions. In all cases the correlation

of the two sources and their source variance should be checked prior to folded versus one-way path measurements.

APPENDIX A

DISTINCTION BETWEEN THE VARIANCE OF THE NORMALIZED INTENSITY AND THE NORMALIZED LOG INTENSITY

The following development will serve to illustrate the intensity dependence in the variance of a normalized variable compared to the lack of an intensity dependence in the variance of the log of a normalized variable.

The variance of a normalized variable, ℓ, is given by

$$\sigma_\ell^2 = \langle \ell^2 \rangle - \langle \ell \rangle^2 \tag{A-1}$$

Let

$$y = I/I_o \tag{A-2}$$

where

y = normalized intensity,

I = intensity,

I_o = average intensity,

and

$$y' = I. \tag{A-3}$$

Then, from equation A-1 the variance of the normalized intensity is

$$\sigma_y^2 = \langle (I/I_o)^2 \rangle - \langle I/I_o \rangle^2 \tag{A-4}$$

Because the average intensity is a constant, equation A-4 can be written as

$$\sigma_y^2 = \frac{1}{I_o^2} [\langle I^2 \rangle - \langle I \rangle^2] \tag{A-5}$$

which, from equation A-1 and A-3 is

$$\sigma_y^2 = \frac{\sigma_{y'}^2}{I_o^2} \tag{A-6}$$

thus demonstrating the inverse square of the average intensity dependence on the variance of the normalized intensity.

For the case of the variance of the log of the normalized intensity, let

$$x = \log \left(\frac{I}{I_o}\right) \tag{A-7}$$

where x = log of the normalized intensity;

furthermore

$$x = \log I - \log I_o$$

and

$$x = x' - A \tag{A-8}$$

where $x' = \log I,$ (A-9)

$A = \log I_o$, which is a constant.

Then, from equation A-1, the variance of the log of the normalized intensity is

$$\sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2 \tag{A-10}$$

and from equation A-8

$$\sigma_x^2 = <(x' - A)^2> - <(x' - A)>^2 \tag{A-11}$$

$$= <x'^2> - 2A <x'> + A^2 - <x'>^2 + 2A <x'> - A^2$$

$$= <x'^2> - <x'>^2 \tag{A-12}$$

From equations A-1 and A-9 this is

$$\sigma_x^2 = \sigma_{x'}^2$$

thus having no dependence on the average intensity.

APPENDIX B

DATA

SOURCE VARIANCE MEASUREMENTS 8 JANUARY 1982

RUN #	HeNe SIGNAL (volts)	GaAs SIGNAL (volts)	HeNe σ^2_{IN} ($x10^{-4}$)	GaAs σ^2_{IN} ($x10^{-4}$)
1	.956	1.341	1.49	7.78
2	.719	1.512	1.54	7.29
3	2.039	1.454	1.26	7.02
4	1.358	1.754	1.23	6.66
5	1.552	.983	2.72	4.60
6	1.872	.563	2.78	6.14

HeNe AND GaAs CORRELATION 26 JANUARY 1982

RUN	BIAS (volts)	SLOPE (a)	$b(x10^{-3})$	CORRELATION COEFFICIENT
1	0.11	1.46	-4.22	.836
2	0.50	1.43	-0.33	.764
3	1.00	1.15	5.33	.861
4	1.46	1.32	-1.40	.927
5	2.00	0.95	7.14	.751
6	2.25	1.39	-1.57	.918
7	2.50	1.67	-6.25	.973

ONE-WAY VERSUS FOLDED PATH 27 FEBRUARY 1982-4 MARCH 1982

D (cm)	y_o	$<\sigma_s^2>(X\ 10^{-2})$	$<\sigma_F^2>(X\ 10^{-2})$	R	DATE	TIME	WEATHER
0	0.00	1.80	14.80	8.23	3-4-82	1237-1245	clear
20	1.00	0.09	0.57	6.19	2-27-82	1626-1633	partly cloudy
40	2.00	0.41	2.51	6.12	3-3-82	1447-1454	partly cloudy
70	3.50	1.29	5.63	4.35	2-27-82	1239-1247	clear
105	5.25	0.97	3.12	3.22	2-27-82	1053-1100	partly cloudy

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